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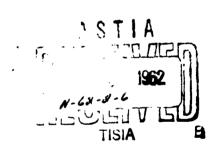
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ELASTIC-PLASTIC DEFORMATION OF A SINGLE GROOVED FLAT PLATE UNDER LONGITUDINAL SHEAR

MICHAEL F. KOSKINEN

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DECEMBER 1961



AERONAUTICAL SYSTEMS DIVISION

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DECEMBER 1961

DIRECTORATE OF MATERIALS AND PROCESSES CONTRACT No. AF 18(600)-957 PROJECT No. 7351

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by the Department of Mechanical Engineering, Massachusetts Institute of Technology, under Contract No. AF 18 (600)-957. The contract was initiated under Project No. 7351, "Metallic Materials," Task No. 73521, "Behavior of Metals." The work was monitored by the Metals and Ceramics Laboratory, Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. D. M. Forney, Jr. acting as project engineer.

This report covers the period of work from September 1959 to September 1961.

ABSTRACT

The development of the plastic strain in a V-grooved flat plate under longitudinal shear was followed from the elastic through the partially plastic to the fully plastic condition for a non-strainhardening material. The region of plastic flow develops monotonically. Adjacent to the zone of deformation in the fully plastic case there is a region where limited plastic deformation has occurred.

The results for the growth of the plastic zone were compared with predictions based on the elastic-plastic solution for an infinite plate and the elastic solution for a finite plate. Agreement is good at low stress levels. At high stress levels, a relatively simple empirical equation, satisfying overall equilibrium, is proposed. Predictions based on elasticity theory alone are shown to be seriously in error.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. Trapp

Chief, Strength and Dynamics Branch Metals and Ceramics Laboratory Directorate of Materials and Processes

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I. INTRODUCTION

For an understanding of fatigue it is desirable to know the distribution of plastic yielding at the tip of a groove or growing fatigue crack. Since problems in longitudinal shear are more readily solved than others, it was decided to study a circumferentially notched, thinwalled tube loaded in torsion, which could be idealized as a grooved plate loaded in longitudinal shear, as shown in Fig. 1. The plate, containing an infinite V-groove in its face, is loaded with a shear stress parallel to the groove. The plate thickness is t, the groove depth is c, and the semi-groove angle is α . The material is elastic-plastic, non-strainhardening with a yield stress in shear of k.

II. ELASTIC-PLASTIC ANALYSIS

Consideration of the case of an infinitely thick plate, given by Hult and McClintock (1956), or of the limiting case of torsion as given by Prager and Hodge (1951), leads one to postulate displacement only in the direction of the axis of the groove. The equations of equilibrium are satisfied if the components of stress are set equal to derivatives of a potential function:

$$T_{xz} = \frac{\partial \phi}{\partial y}$$
; $T_{yz} = -\frac{\partial \phi}{\partial x}$. (1)

In the elastic region Hooke's Law and the dependence of strains on the one component of displacement then lead to the familiar Laplace equation for the stress potential ,

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad , \tag{2}$$

subject to the boundary condition,

$$\phi(x,y) = \int \left(\frac{\partial \phi}{\partial x} dx + \frac{\partial \phi}{\partial y} dy\right) = \int \left(\mathcal{T}_{xz} dy - \mathcal{T}_{yz} dx\right)^{(3)}$$

integrated around the boundary of the elastic region.

Equation 2 with its associated boundary condition, Eq. 3, applies only in the region where Hooke's Law is satisfied and can be solved only with a knowledge of the position of the elastic-plastic boundary. (More precisely, it is not the plasticity but the non-linearity of the stress strain relation which is critical in determining this boundary,

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but the two conditions are identical for the material considered here.) The need to know the elastic-plastic boundary is avoided by transforming from space coordinates to stress coordinates. Since the Jacobian of and \mathcal{T}_{YZ} with respect to x and y is non-zero, the continuity and equilibrium equations can be written as

$$\left(\frac{\partial x}{\partial \mathcal{T}_{YZ}}\right)_{\mathcal{T}_{XZ}} - \left(\frac{\partial y}{\partial \mathcal{T}_{XY}}\right)_{\mathcal{T}_{YZ}} = 0$$

$$\left(\frac{\partial x}{\partial \mathcal{T}_{XZ}}\right)_{\mathcal{T}_{YZ}} + \left(\frac{\partial y}{\partial \mathcal{T}_{YZ}}\right)_{\mathcal{T}_{XZ}} = 0$$
(4)

The second of these will be identically satisfied if the coordinates are set equal to the partial derivatives of a potential with respect to the components of stress:

$$x = \left(\frac{\partial \psi}{\partial \mathcal{T}_{YZ}}\right) \mathcal{T}_{XZ}$$

$$y = -\left(\frac{\partial \psi}{\partial \mathcal{T}_{XZ}}\right) \mathcal{T}_{YZ}$$
From Eq. 4, the coordinate potential ψ then must satisfy Laplace's

equation,

$$\frac{\partial^2 \psi}{\partial \mathcal{T}_{XZ}^2} + \frac{\partial^2 \psi}{\partial \mathcal{T}_{YZ}^2} = 0 , \qquad (6)$$

subject to the boundary condition

$$\psi(\tau_{xz}, \tau_{yz}) = \int \left(\frac{\partial \psi}{\partial \tau_{xz}} d\tau_{xz} + \frac{\partial \psi}{\partial \tau_{yz}} d\tau_{yz}\right)
= \int \left(\frac{\tau_{xz}, \tau_{yz}}{\partial \tau_{xz}} - y d\tau_{yz}\right) .$$
(7)

This transformation and the resulting houndary conditions are shown in Fig. 7. In integrating around the elastic-plastic boundary it must be noted that the resultant stress is equal to the yield stress and is normal to a position vector from the tip of the groove. The entire boundary except the magnitude of the stress at the free surface opposite the groupe (\mathcal{T}_b) is known. However, from the continuity of stress in space it can be shown that ($\partial \psi/\partial \mathcal{T}_{\times \mathbf{Z}}$) is continuous in the \mathcal{T}_{YZ} - direction across the point ($\mathcal{T}_{XZ} = 0$, $\mathcal{T}_{YZ} = \mathcal{T}_b$), which is sufficient information to uniquely determine a solution.

Due to this indeterminate boundary condition, the author was not able to find a closed form, analytic solution to the problem. Therefore the solution was carried out by machine computation using relaxa-

These computations were performed in part at the M. I. T. Computation Center, Cambridge, Mass., and completed at the University Mathematical Laboratory, Cambridge, England.

tion techniques plus a provision for satisfying continuity of $(\partial \psi / \partial \gamma_{YZ})$ across $\gamma_{YZ} = \gamma_b$. To simplify computation, the sector-shaped area of the stress plane was mapped conformally into a semi-infinite strip. Since the zero stress point of the stress plane is a singular point of this transformation, the boundary there was replaced by a small circle of radius $\gamma_{co} \exp(-3\pi/2)$ and ψ was simply called zero on this circle. The number of cycles to obtain proper convergence and the accuracy of the finite difference approximations were determined as outlined by Crandall (1956). The degree of convergence was checked by performing extra cycles in one case. The slopes of the potential function are accurate to about 5% and are on the low side of the correct value. The results of these computations are shown in Figs. 3 through δ .

Hult and McClintock (1956) have shown that in the plastic zone, the strain consists of a single shear component normal to the position vector, \mathbf{f} . This shear component is given in terms of the yield strain, $\mathbf{y}_{\mathbf{y}} = \mathbf{k}/\mathbf{G}$, and the distance to the plastic-elastic boundary (\mathbf{R}), measured through the point in question, by

$$\gamma_{\Theta Z} = \gamma_{y} R/r$$
 (8)

Therefore since the elastic-plastic boundary is known, the strain distribution in the plastic zone can be determined.

It can be seen from Fig. ℓ that for any element, the strains are monotonically increasing functions of the applied load. Therefore the same result is obtained for either non-linearly elastic or elastic-plastic material.

Once the fully plastic state is reached, all further deformation takes place on the plane y = 0, as predicted by a rigid-plastic analysis. It is observed that adjacent to the plane of deformation in the fully plastic state, a region of limited deformation exists as suggested by Hill (1950).

III. COMPARISON WITH ELASTIC ANALYSIS

Since numerical computations are time consuming and do not afford a compact summary of results, it is well to inquire how closely these results might be anticipated from an elastic analysis coupled with the elastic-plastic analysis of Hult and McClintock (1956) for a plate of

infinite thickness.

As shown by Milliams (1957) for zero-angle notches under tension or transverse shear, the stress distribution near the tip of the notch in a body of arbitrary shape can be characterized by a single parameter. Similarly, for a zero-angle groove, or crack, under longitudinal shear, Mult and McClinton (1951) found the elastic stress distribution to be

$$T_{\Theta Z} = K_3 r^{-1/2} \cos \frac{\Theta}{2} ; T_{rZ} = K_3 r^{-1/2} \sin \frac{\Theta}{2} .$$
 (9)

For the infinite clate, the constant \cdot , is liven in terms of the stress at infinity (τ_∞) and the cruck death (c) by

$$K_{3\infty} = \mathcal{T}_{\infty} \left(c/2 \right)^{1/2} \tag{10}$$

For an abstrict with yield attempth in shear of k, the radius of the plastic some each be so and from the case of a crack in an infinite solid to be given in terms of the clastic atreas intensity factor, K3, of the clastic solution by

$$R = 2K_3^2/k^2 = c(\tau_{\infty}/k)^2$$
. (11)

The shaped street intensity factor for the slate of finite thickness, R_{22} , is found in a transforation shallow to that used by Mestermand ([3]) or the gran of a series of errors in a plate under tension. The transforation pickles approarion for plate thickness identical to that Join 1 to tester wind, which is also recommended by the ASTI (1960) for sonsion of sin used similar width:

$$\left(K_{3t}/K_{3\infty}\right)^2 = \frac{2\pi}{\pi c} \tan \frac{\pi c}{2t} . \tag{12}$$

In the absence of a wor, this electric correction factor is exact. In the case of a later transform is is bot, because normal atress exists on the lines of improvement to are a in Mashengaard's analysis, but not on the Internal comparise of the actual contrate sheets.

In the argo of chaptic flow, as the a plied stress is increased the lastic and vota more radially than riven by Eqs. 11 and 12. An a proximate equation can be form thated by noting that when the minimum section local as fully classic, equilibrium requires that the applied stress by $T_0 = -(t-c)/t$. This can be achieved by adding a correction term to Eqs. 11 and 13:

$$R_0 = C \left(\frac{\tau_{\infty}}{k}\right)^2 \left(\frac{2t}{\pi c} \tan \frac{\pi c}{2t}\right) + C \left(1 - \sqrt{1 - \left(\frac{\tau_{\infty}}{k} \frac{t}{t - c}\right)^N}\right) . \tag{13}$$

Choosing the exponent on the stress term to be 5, and the constant C to give the proper limit gives

$$C' = (t-c)(1 - \frac{2(t-c)}{\pi t} \tan \frac{\pi c}{2t})$$
 (14)

The results of the approximate relation given by Eq. 13 are plotted in Figs. 3 through 5 and give satisfactory agreement with the more exact numerical solution. It is also of interest to compare these results with the assumption that the plastic zone extends to the point where the stress calculated on an elastic basis reaches the yield stress, as recommended by the ASTA (1960). In making the correction for the finite width of a plate, they suggest that the effective crack length should be taken to be the actual crack length whis the radius from the tip of the crack to the elastic-plastic boundary directly ahead of the crack, $c+R_{\rm O}$. These ideas lead to the equation

$$R_0 = \frac{c}{2} \left(\frac{\tau_{\infty}}{k} \right)^2 \frac{2t}{\pi c} \tan \frac{\pi (c + R_0)}{2t} . \tag{15}$$

As shown in Figs. 3 through 5, this approximation is unsatisfactory. In the first place, at low stress levels it was shown by Hult and McClintock (1956) that this type of approximation gave results low by a factor of two. On the otherhand, at high stress levels the equation is unsatisfactory because it implies that when the plastic zone reaches all the way across the plate, the load carrying capacity has dropped to zero. Even without the appearance of the term for the radius of the plastic zone in the correction for Minite place width, the equation fails to satisfy equilibrium in the fully plastic case. Since this objection holds in the case of a sheet under tension as well as a plate under shear, the tensile analog of Eq. 13 is to be preferred.

A further disadvantage to the above assumption, that the boundary of the plastic zone is the point at which the elastic stress distribution reaches the yield stress, is seen on noting that such an assumption would indicate plastic flow occurring along the flamb of the groove, whereas as shown in Figs. 6 through 3, the plastic zone actually lies entirely ahead of the crack.

IV. CONCLUSIONS

- 1) In the fully plastic case, the strain in a singly-grooved flat plate under longitudinal shear is concentrated along the minimum section. As the plastic flow develops, however, small scale plastic strain occurs in a monotonically increasing region on either side of the plane of minimum cross section.
- 2) The extent of the plastic zone ahead of the groove, R_0 , is given in terms of the plate thickness t, the crack length or groove depth x, the nominal applied stress, 7_{∞} , and the yield stress in shear, k, by the equation

$$R_0 = c \left(\frac{\tau_{\infty}}{k}\right)^2 \frac{2t}{\tau c} \tan \frac{\tau c}{2t} + c' \left(1 - \sqrt{1 - \left(\frac{\tau_{\infty}}{k} \frac{t}{t-c}\right)^5}\right),$$

where the constant C, chosen to satisfy equilibrium in the fully plastic case, is

$$C' = (t-c)\left(1 - \frac{2(t-c)}{\pi t} \tan \frac{\pi c}{2t}\right).$$

- 3) A corresponding equation, derived by a method recommended by the ASTM, is in error by a factor of two at low stress levels, and is even qualitatively incorrect at high stress levels.
- 4) Within the plastic zone, the strain is given in terms of the radius to the elastic-plastic boundary by

$$\gamma_{\Theta Z} = \frac{k}{G} \left(\frac{r}{R} \right)$$
.

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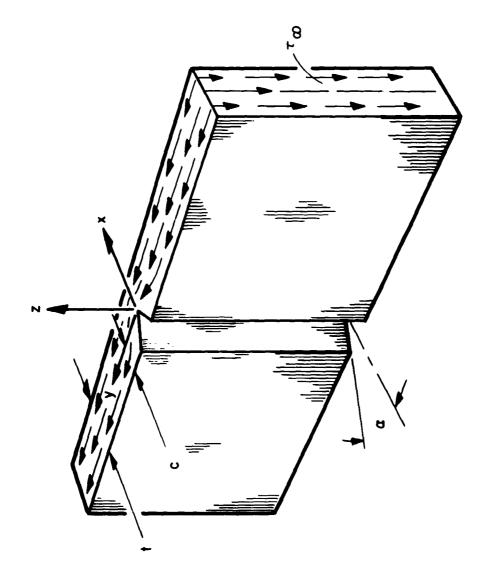
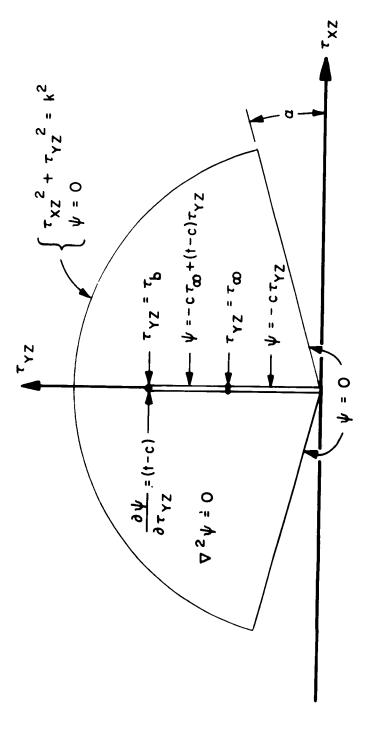


FIG. 1 GROOVED PLATE LOADED IN LONGITUDINAL SHEAR.



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FIG. 2 ELASTIC-PLASTIC PROBLEM IN STRESS COORDINATES WITH BOUNDARY CONDITIONS.

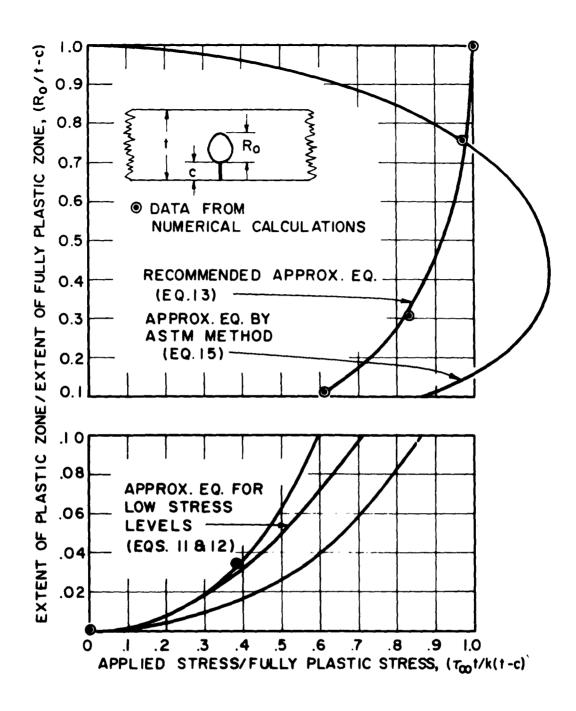


FIG.3 EXTENT OF PLASTIC ZONE VS. APPLIED LOAD, WITH APPROXIMATE EQUATIONS (c/t = 1/4).

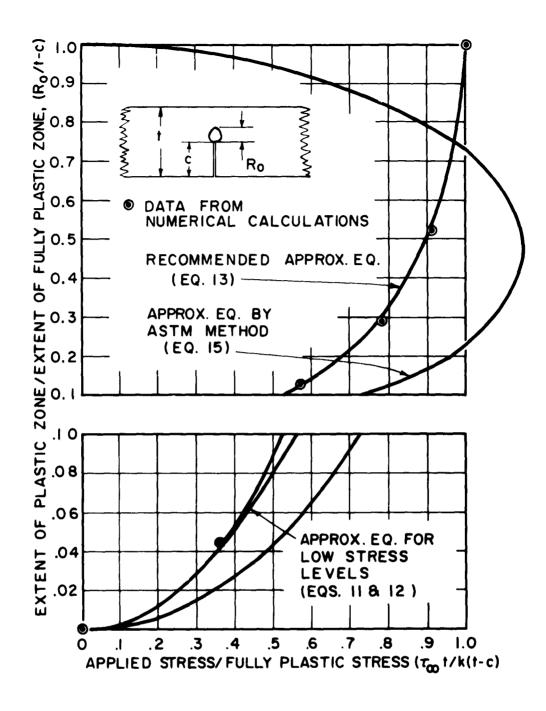


FIG. 4 EXTENT OF PLASTIC ZONE VS. APPLIED LOAD, WITH APPROXIMATE EQUATIONS (c/t=1/2)

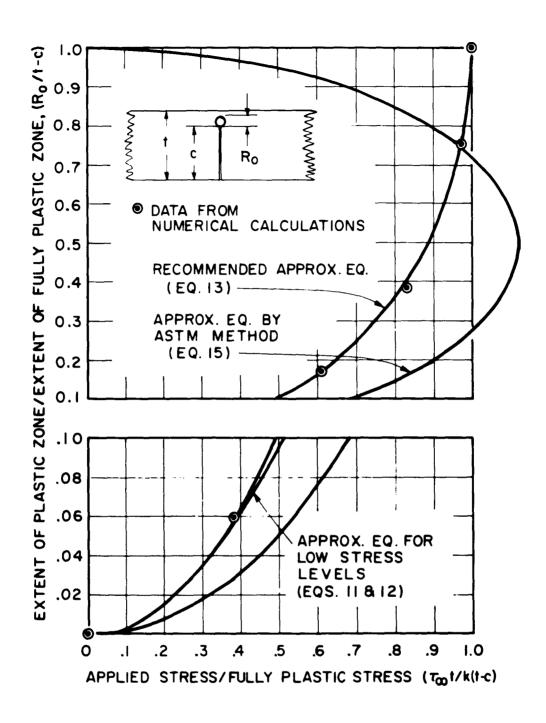
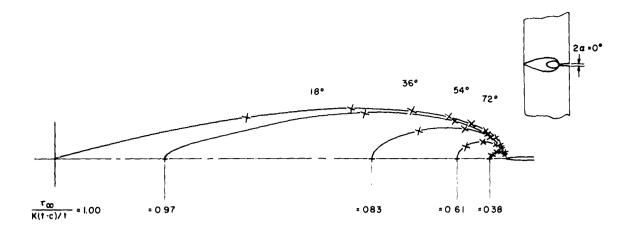
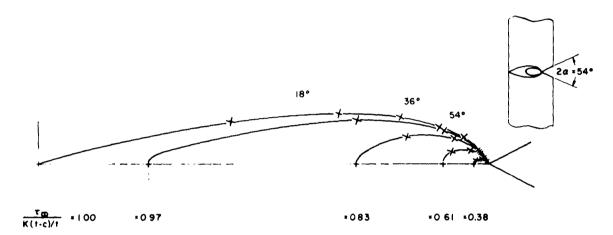


FIG. 5 EXTENT OF PLASTIC ZONE VS. APPLIED LOAD, WITH APPROXIMATE EQUATIONS (c/t = 3/4)





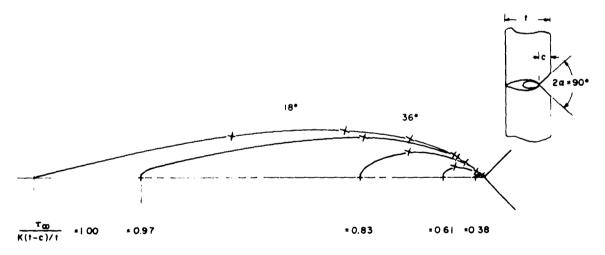
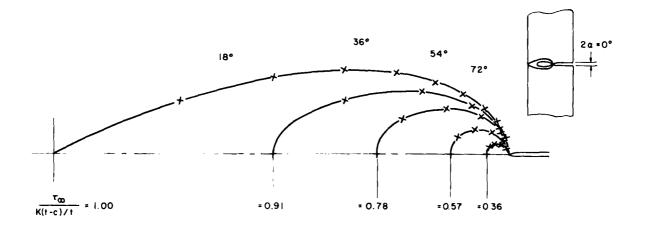
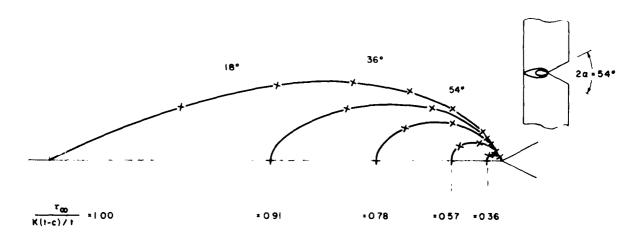


FIG. 6 ELASTIC - PLASTIC BOUNDARY AT VARIOUS APPLIED LOADS AND NOTCH ANGLES FOR c/t = 1/4.





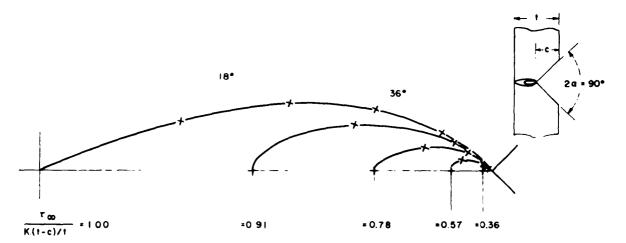


FIG 7 ELASTIC - PLASTIC BOUNDARY AT VARIOUS APPLIED LOADS AND NOTCH ANGLES FOR c/t = 1/2

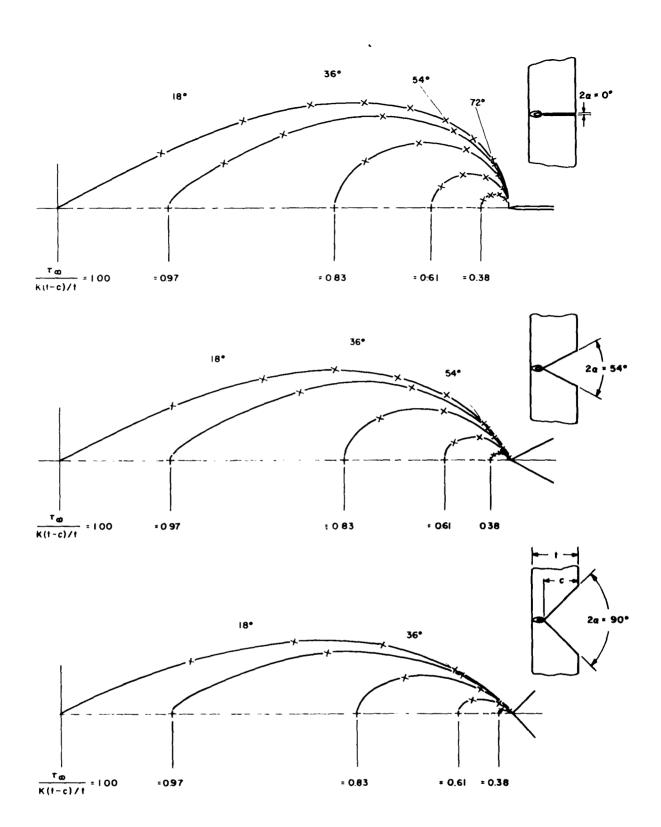


FIG 8 ELASTIC-PLASTIC BOUNDARY AT VARIOUS APPLIED LOADS AND NOTCH ANGLES FOR c/t = 3/4.

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Cambridge, Name, Electronical DEFORMATION OF TROUBOLDS. ANTON CF A SINGLE GROOVED FLAT FLATE CHOSEN LONGITUDINGL SHEAR, by Michael F. Koekknen, December 1961, 15p., incl. figs. (Froject 7951; Inch 7952) (ASD IR GL-63) (Contract AF 18 (600)-957)	Inclassified report The development of the lastic strain in a formoved flat plate under longitudinal sient was followed from the elastic through the partially plastic to the fully plastic condition for a non-strainardening material. The region of plastic flow develops monotonically, adjacent to the	ZONE OF MENOTIN WER TULLY PLANTS	plastic deformation has occurred. The results for the grouth of the plastic zone were compared with predictions based on the elastic solution for an infinite plate. Agreement is good at low stress levels. At high stress levels, a thinking the simple empirical equation, as satisfying overeal equalitation, is proposed. Predictions hased on elasticity theory alone are shown to be seriously in error.	

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